Comparative evaluation of steel, glass and polypropylene fiber reinforced shotcretes for tunnel lining

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ABSTRACT: The present paper deals with the use of different types of fiber to reinforce shotcrete for tunnel linings. Experimental investigations were performed on steel (SF), glass (GF) and polypropylene fibers (PF) reinforced concretes and shotcrete (manufactured with a silicate based set-accelerating admixture) in order to compare rheological and mechanical behavior of fiber reinforced mixtures with respect to plain concrete (without fibers: PL). No influence of fibers was observed on rheological properties. Shotcrete rebound was not affected by the type of fiber, but it seems to be closely related to the dosage of set-accelerating admixture. The mechanical properties were strongly influenced by both the casting method (casting for concretes and spraying for shotcrete) and the dosage of set-accelerating admixture rather than the type and dosage of fibers used.

1 INTRODUCTION

Concrete is a brittle material with a low tensile strength and a natural tendency to contract and expand with moisture and temperature variations. Stress induced by restrained shrinkage promotes crack in the concrete matrix. Most random cracks that appear at an early age, although unsightly, rarely affect the structural integrity of concrete elements. Often, cracks represent only an aesthetic problem, but sometimes, if not controlled, drying shrinkage can lead to serviceability problems, such as excessive deflections on slab, and durability problems, such as freeze-thaw deterioration and corrosion of rebars. In order to limit the crack width, concrete is therefore normally reinforced with steel bars. However, the use of steel bars doesn't eliminate the appearance and the evolution of cracking. In fact, the disposition of steel bars along the principal direction of stress does not always prevent the crack development. For these reasons, it is becoming increasingly popular to reinforce the concrete with small and randomly distributed fibers of different materials. Compared with steel bar, the fibers arrange themselves on three-dimensional way inside the cement matrix and they are able to absorb the tensile stress in any direction. Therefore, the fibers could limit the cracks width and increase the energy absorption capacity (toughness) of the material. In particular, fibers determine a considerable improvement in the post-cracking behavior of concrete [Coppola et al. 2011]. Plain concrete fails suddenly once the deflection corresponding to the ultimate flexural strength is exceeded; on the other hand, fiber reinforced concrete continue to sustain considerable loads even at deflections considerably in excess to that of the plain concrete.
Since the turn of the last century, the use of fibers has increased. The first fibers to be used were those of asbestos to produce precast slab. Steel fibers appear only in the late '40s in the U.S.. Thereafter, glass, organic, cast-iron, brass and polyolefin [Collepardi et al. 1991] fibers were developed. Currently, concrete is reinforced by using steel, glass, polypropylene or acryl-nitrile fibers [Coppola 2008]. Since many years, fiber reinforced shotcrete (FRS) has been used in tunneling applications. Using fiber reinforced

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mixtures, the steel reinforcement should be eliminated on the tunnel lining, reducing the risk for the worker and increasing the safety [Zeidler and Jäger 2007]. Compared to plain concrete, fiber-reinforced concrete is tougher and more resistant to impact, permitting to control the local detachment of tunnel linings [Zeidler and Jäger 2007, Coppola 2001, Zaffaroni et al. 2000]. Unfortunately, lack of International Building Codes limits the use of fiber-reinforced concrete. Now, *fib* (*Fédération International du Béton*) is updating CEB-FIP Model Code 90, adding two sections (material and structural behavior) about fiber reinforced concrete.
In this paper, results of an experimental study that compares rheological and mechanical properties of plain and reinforced concretes/shotcretes with glass, steel and polypropylene fibers are presented.

2 MATERIALS AND EXPERIMENTAL WORK

2.1 Materials

2.1.1 *Cement*

A Limestone Portland Cement (CE II/A-LL 42.5R) according to EN 197-1 provided by Italcementi Group S.p.A. was used. The chemical composition of cement is shown in Table 1.

Table 1. Chemical composition (% by mass) of the cement (CE II/A-LL 42.5R).

Loss On Ignition (L.O.I.) at 500°C			0.88
SiO_2	19.31	MgO	2.38
Al_2O_3	4.31	SO_3	2.96
Fe_2O_3	2.28	Na_2O	0.29
TiO_2	0.14	K_2O	0.86
CaO	61.08	Cl	0.06

2.1.2 *Aggregates*

Coarse-grained sand (40% of the total mass of the aggregates) and crushed sand (25%) were used as fine aggregates. In addition crushed stone (max size 8 mm) was used as coarse aggregate (35%). A sieve analysis of the fine and coarse aggregates in shotcrete is shown in Table 2. Combined aggregate grading is presented in Fig. 1.

Table 2. Chemical Sieve analysis of aggregates in shotcrete

Square mesh [mm]	**Cumulative per cent passing [%]**			
	crushed sand (25%)	**coarse-grained sand (40%)**	**crushed stone (35%)**	**Total (100%)**
16	100.0	100.0	100.0	100.0
12.5	100.0	100.0	100.0	100.0
8	100.0	100.0	100.0	100.0
4	100.0	99.0	26.0	73.7
2	78.0	87.0	1.7	54.9
1	54.0	69.0	0.5	41.3
0.5	38.0	47.0	0.2	28.4
0.25	25.0	20.0	0.2	14.3
0.063	4.9	1.2	0.2	1.8

2.1.3 *Admixtures*

A polycarboxylate-based superplasticizer was used. The dosage of superplasticizer was 1.4% vs. cement mass. Before spraying, a set-accelerating admixture was added. The dosage of sodium silicate based admixture was in the range 13% - 17% vs. cement mass.

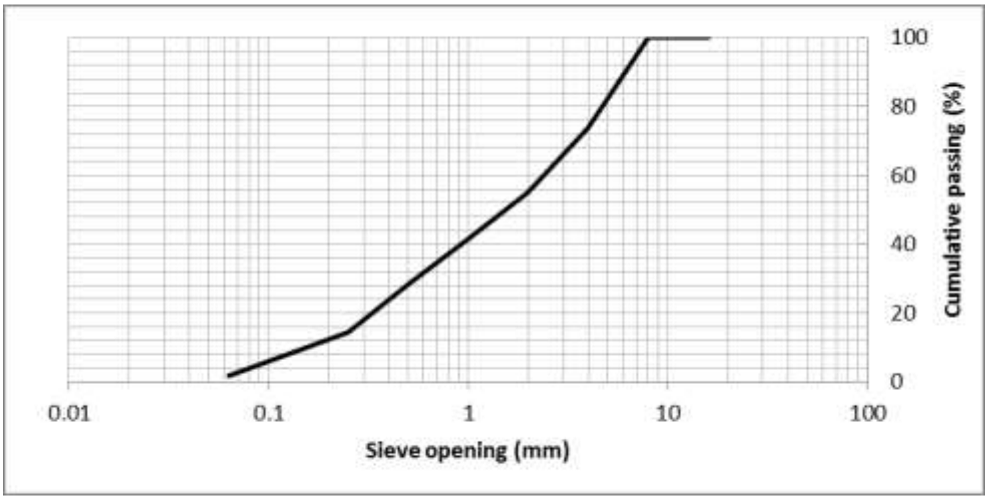

Fig. 1. Combined aggregate grading.

2.2 Concrete mixture

The w/c was fixed equal to 0.44. Workability of plain concrete was measured by slump test according to EN 12350-2 and the consistency class required for the mixture was S5 (slump ≥ 220 mm). The composition of plain concrete without fibers and set-accelerating admixture is shown in Table 3.

Table 3. Composition and principal characteristics of the plain concrete.

INGREDIENTS DOSAGE		
Cement CE II/A-LL 42.5R	kg/m^3	450
Water	kg/m^3	200
Aggregates:		
Crushed sand	kg/m^3	410
Coarse-grained sand	kg/m^3	650
Crushed stone (max size 8 mm)	kg/m^3	575
Superplasticizer	%	1.4
	l/m^3	6.3
Entrapped air	%	2.5
CHARACTERISTICS		
Water/Cement		0.44
Specific mass	kg/m^3	2344

2.3 Experimental

In order to compare the influence of different types and dosages of fiber reinforcement on rheological and mechanical properties with respect to plain concrete/shotcrete

(without fibers: PL), steel fibers (SF), glass fibers (GF) and polypropylene fibers (PF) were added to the mixture. The fiber dosages are shown in Table 4.
The dosage by volume of steel and glass fibers is very similar, consequently, rheological and mechanical properties are directly comparable in order to establish which of the two types of fibers is more efficient. On the other hand, the dosage of polypropylene fibers is lower than that used for the steel and glass fibers (about 37% and 39%, respectively). Therefore, the results discussion has to take into account the lower amount of polypropylene fibers.
During the cast (at 1/5 and 4/5 of the placing), before the addition of set-accelerating admixture, the workability and the specific mass were evaluated in order to investigate the fiber influence on rheological properties of the concrete. After the addition of the set-accelerating admixture, concrete was sprayed. The fiber content and the shotcrete rebound were measured, according to EN 14488-7.

Table 4. Type and dosage of fiber added to plain mix.

Mixture	Fiber type	Specific mass	Fiber dosage	
		kg/m^3	kg/m^3	l/m^3
PL	-	2341	-	-
SF	Steel	2394	38.2	4.4
GF	Glass	2342	11.2	4.7
PF	Polypropylene	2324	3.5	2.9

To evaluate hardened concrete properties, test panels were manufactured, according to EN 14488-1, with and without the addition of set-accelerating admixture. After casting, the panels were immediately wet cured to avoid water evaporation. Afterward the specimens were cured on site condition until cored. For each panel, three cylindrical specimens (d=100 mm, h=100 mm, h/d=1) were obtained and specific mass and compressive strength after 1, 7 and 28 days were measured. Finally, 600 mm x 600 mm panels were manufactured by spraying the set-accelerating admixture in order to evaluate the energy absorption capacity, according to EN 14488-5, after 1, 7 and 28 days. For reference mixture (without fibers), a steel wire mesh (diameter: 6 mm; spacing: 150 mm) was used as reinforcement.

3 TEST RESULTS AND DISCUSSION

3.1 Rheological properties

3.1.1 *Specific mass*

In **Errore. L'origine riferimento non è stata trovata.**, the average values of specific mass of fresh concrete, measured after 1/5 and 4/5 of the dumping (before the set-accelerating admixture addition), are shown.
The values are similar for all the mixtures, independently of the type of fiber. Furthermore, after 30 minutes, the specific mass values don't change. Therefore, fibers don't determine any anomalous air entrapment.

3.1.2 *Workability*

The target workability (S5 according to EN 206-1) was attained without any increase in water demand with respect to the plain concrete for all the fiber reinforced mixtures, independently of the type of fiber. Moreover, no slump loss was noticed after 45 minutes from the end of the mixing procedure (

Fig. 3).

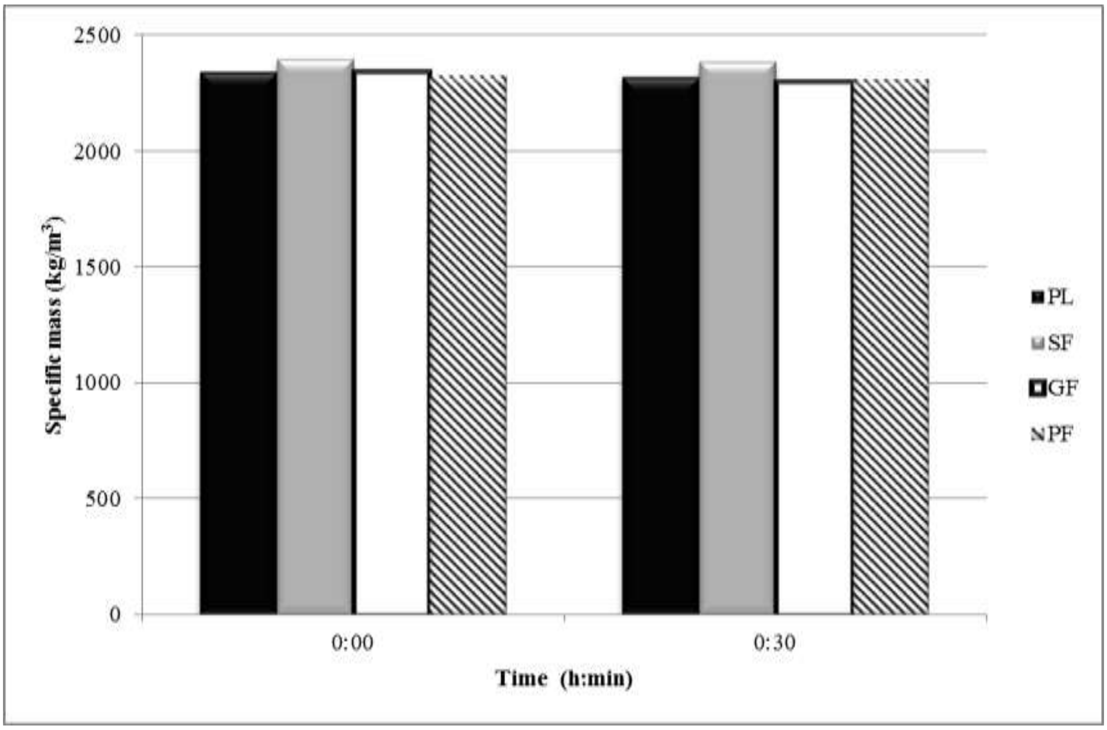

Fig. 2 Specific mass of fresh concrete vs. time.

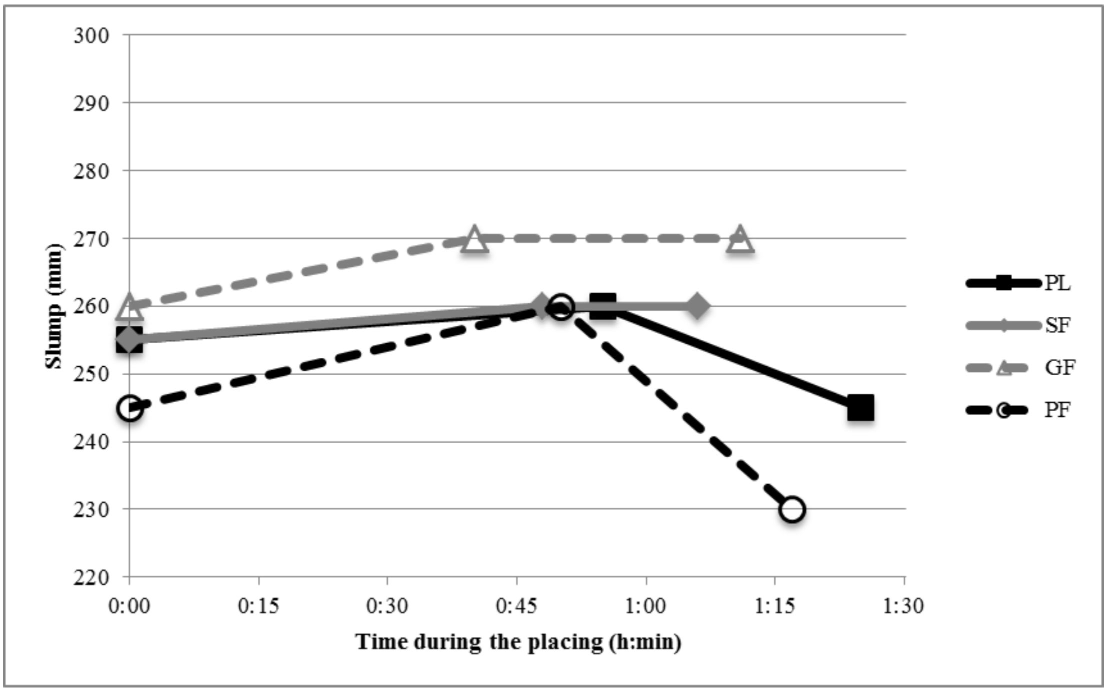

Fig. 3 Slump vs. time.

3.1.3 *Set-accelerating admixture and rebound*

Fig. 4 shows the shotcrete rebound index and the set-accelerating admixture dosage. The dosage of set-accelerating admixture (sodium silicate) was about 13-17% (with respect to cement mass). The lower dosage was used for the steel fiber reinforced shotcrete and the greater one for that containing glass fiber.

The plain and the polypropylene fiber reinforced shotcretes required a similar set-accelerating dosage (about 15%). The shotcrete rebound was very different for the mixtures: it was between 18 and 35%. The lowest value was obtained using glass fibers and the highest with steel fibers. Analyzing the results, it can be observed that the rebound is strictly dependent on set-accelerating dosage, whereas the type of fiber doesn't influence it. An inverse proportionality exists between set-accelerating dosage and rebound: the higher the dosage of set-accelerator the lower the shotcrete rebound. Therefore, the rebound isn't affected by the type and the dosage of fibers, but it seems to be strictly related to the dosage of set-accelerating admixture.

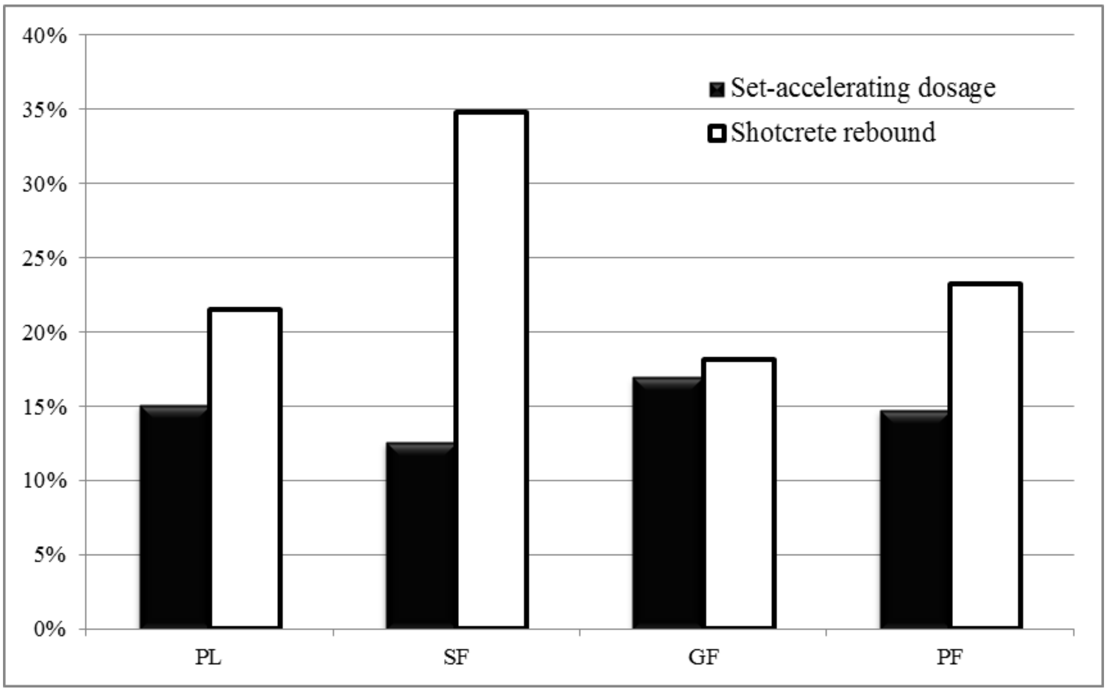

Fig. 4 Set-accelerating admixture dosage and shotcrete rebound.

3.2 Mechanical properties

3.2.1 *Specific mass of hardened mixtures*

The addition of the set-accelerating admixture and the spraying operation determine a reduction of specific mass in the range 2-6% with respect to that of mixtures without sodium silicate, cast by pouring and vibrated, independently of curing time and type of fiber (Fig. 5). Therefore, specific mass is not affected by the fibers. Adding fibers, the specific mass of hardened mixture is substantially equal or higher than that of the reference shotcrete without fibers.

3.2.2 *Compressive strength*

Fig. 6 summarizes the compressive strength values as a function of time for concretes (vibrated) and shotcretes (sprayed) without and with the set-accelerating admixture, respectively.

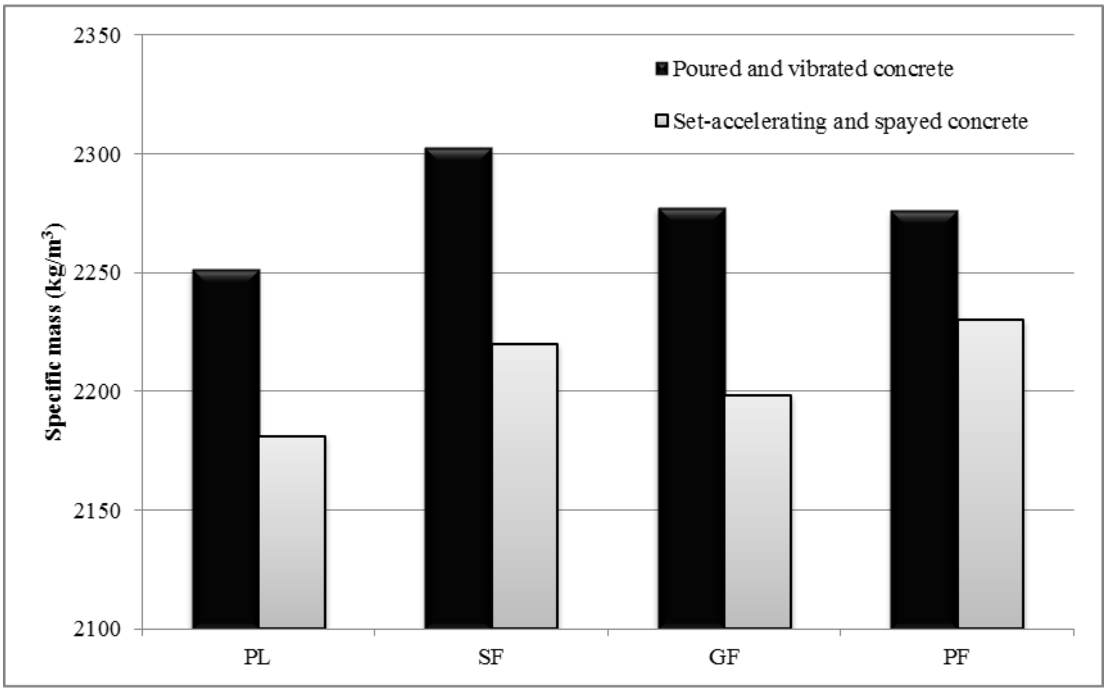

Fig. 5 Specific mass of hardened concretes and shotcretes after 28 days.

After 1 day, the compressive strength of shotcrete with the addition of set-accelerating admixture is higher (50 to 85%) than that of poured and vibrated concrete mixtures without the sodium silicate, independently of the fiber reinforcement. Therefore, the use of set-accelerating admixture permits to compensate the porosity increase (Fig. 5) due to spraying procedure.

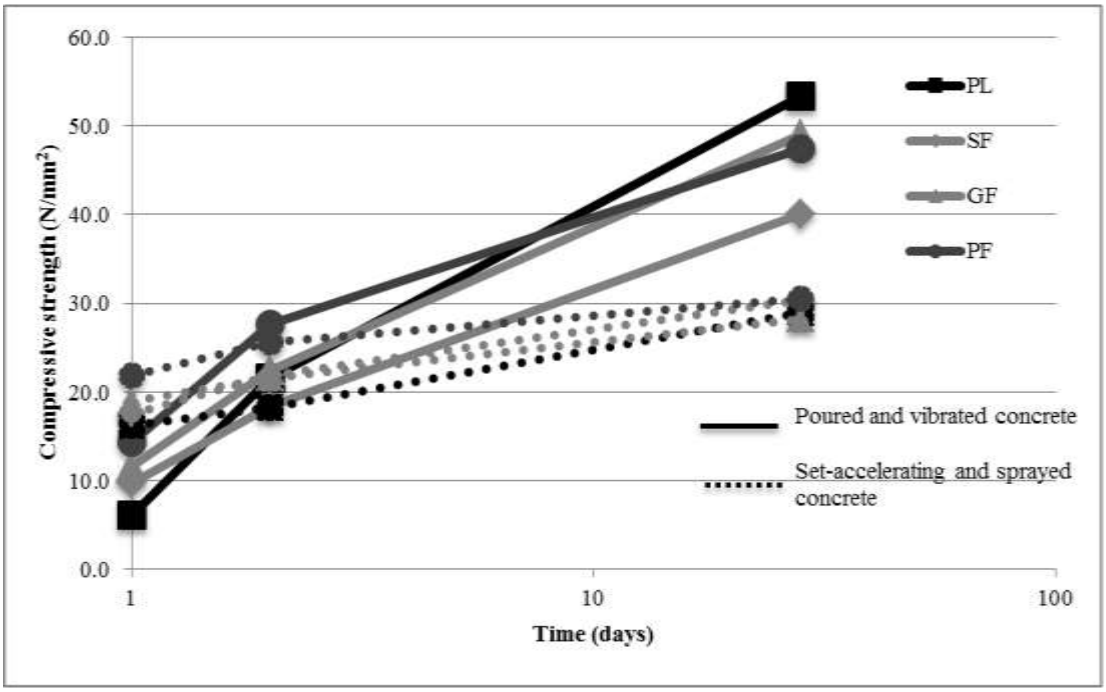

Fig. 6 Compressive strength vs. time for specimens with and without set-accelerating admixture.

At 2 days compressive strength of all the mixtures is very similar. So, the positive effect of set-accelerating admixture is equal to the negative effect due to the increase in porosity as a consequence of spraying. After 28 days, shotcretes with sodium silicate present a lower compressive strength, between 25 and 45% than that of vibrated concrete without set-accelerating admixture. In particular, a minor decrease (about 25%) is observed for SF shotcrete, manufactured using the lowest set-accelerating admixture dosage. On the contrary, the greater gap in the compressive strength was detected for GF shotcrete, containing the highest set-accelerator dosage. Hence, the compressive strength values depend strictly on set-accelerating dosage rather than type and dosage of fibers. In general terms, considering that the reduction of compressive strength due to spraying is about 5% for each per cent of specific mass decrease and taking into account that the specific mass reduction is about 2-6%, the reduction of compressive strength due to spraying should be about 10-30%. So, if the total compressive strength decrease is between 25 and 45%, the set-accelerating effect on reduction of mechanical properties is about 15%. In conclusion, data confirms that the compressive strength value depends on casting method and set-accelerating dosage more rather than type and dosage of fiber reinforcement.

3.2.3 *Punching*

The results of punching tests (Fig. 7) are shown in terms of deformation energy of the panels manufactured with set-accelerated shotcretes containing fibers and with the set-accelerated reference concrete reinforced by a steel wire mesh (diameter: 6 mm; spacing: 150 mm).

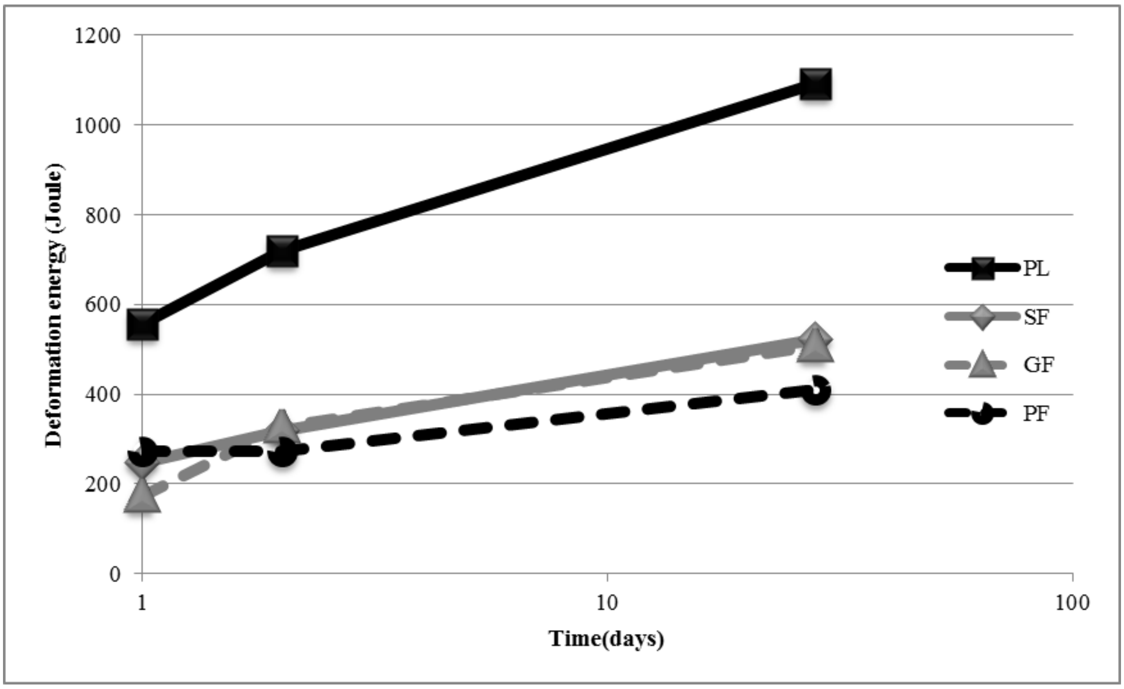

Fig. 7 Deformation energy vs. time.

Data indicate that fibers don't guarantee the same performance of steel mesh. In fact, after 1 day, the shotcrete reinforced by steel mesh exceeds the minimum value of 500 Joule required by the norm. On the contrary, this value is attained using steel and glass fiber only at 28 days. The polypropylene fiber reinforced shotcrete panel doesn't achieve the threshold value even after 28 days. Concerning polypropylene fibers, it is important to underline that the PF mixture was manufactured with a fiber dosage (2.9 l/m^3) lower than that used for SF and GF shotcretes (respectively 4.4 and 4.7 l/m^3). In conclusion, results point out the better punching behavior of steel reinforced shotcrete with respect to fiber reinforced mixtures. This could be explained considering that the shotcrete behavior on punching test depends not only on the fiber type and dosage, but overall on the matrix quality. In this research, the addition of set-accelerating admixture has caused a worsening of matrix quality and consequently a reduction of the bonding between fibers and shotcrete. Thus, the toughness behavior and the energy absorption of fiber reinforced mixtures decrease and the gap between these and the steel mesh reinforced shotcrete dramatically increases.

4 CONCLUSIONS

The present paper compares rheological and mechanical properties of plain and glass, steel and polypropylene fiber reinforced concretes and shotcretes for tunnel lining.
Experimental results indicate that:

- The addition of fiber doesn't influence specific mass, slump and workability retention with respect to plain concrete (PL), independently of type and dosage of fibers.
- An inverse proportionality exists between set-accelerating admixture dosage and shotcrete rebound: the higher the dosage the lower the rebound. Therefore, the rebound isn't affected by fibers, but it seems to be strictly related to the dosage of set-accelerating admixture.

- Adding fibers, the specific mass of hardened fiber reinforced mixtures is substantially equal or higher than that of reference concrete/shotcrete without the fibers.
- Compressive strengths at 1 day are higher for shotcrete manufactured using sodium silicate, meaning that this admixture compensates for the porosity increase due to the spraying application.
- Specific mass of hardened shotcrete and compressive strength at 28 days decrease adding set-accelerating admixture, independently of fiber reinforcement. After 28 days, shotcretes with sodium silicate present a compressive strength lower (in the range 25-45%) than that of vibrated concrete without set-accelerating admixture. In particular, reduction of compressive strength as a consequence of spraying is about 10-30%. The negative effect on strength of set-accelerator is in the order of 15%.
- The toughness behavior and the energy absorption of fiber reinforced shotcrete are lower than that of steel reinforced mixture. Worsening of matrix quality as a consequence of set-accelerator addition reduces in a more significant manner bond of short reinforcing fibers rather than that of a continuous reinforcement as that represented by the steel mesh.

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